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Kaluza-Klein Dark Matter and the Positron Excess

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The excess of cosmic positrons observed by the HEAT experiment may be the result of Kaluza-Klein dark matter annihilating in the galactic halo. Kaluza-Klein dark matter annihilates dominantly into charged leptons that yield a large number and hard spectrum of positrons per annihilation. Given a Kaluza-Klein dark matter particle with a mass in the range of 300-400 GeV, no exceptional substructure or clumping is needed in the local distribution of dark matter to generate a positron flux that explains the HEAT observations. This is in contrast to supersymmetric dark matter that requires unnaturally large amounts of dark substructure to produce the observed positron excess. Future astrophysical and collider tests are outlined that will confirm or rule out this explanation of the HEAT data.

In 1994 and 1995, the High-Energy Antimatter Telescope (HEAT) reported an excess of cosmic positrons, peaking in the range of 7-10 GeV, and continuing to higher energies [1]. In 2000, an additional HEAT flight confirmed this observation [2]. Many previous experiments, although less precise, also recorded a larger than expected positron flux above about 10 GeV (see Ref. [1] and references therein). The study of the astrophysical production of positrons [3] has been thoroughly investigated [4], with the conclusion that the ratio of cosmic positrons to electrons above about 10 GeV is higher than is suggested by secondary production in a model of a diffusive halo.

Galactic positrons potentially provide an interesting probe of particle dark matter annihilation in the galactic halo [5]. The prospects for supersymmetric dark matter annihilation producing positrons, including within the context of the HEAT observations, have been extensively discussed, for example, in Refs. [5, 6, 7, 8, 9]. In supersymmetric models, the lightest supersymmetric particle is stable (with exact R-parity) and is usually a neutralino. Neutralino annihilation directly to $\ell^+\ell^-$ is, however, helicity-suppressed, and thus positrons arise only through cascade decays such as from decays of gauge bosons. This typically results in a rather soft spectrum of positrons and is, therefore, hard to reconcile with the positron flux and spectrum observed by HEAT without an unnaturally large degree of clumpiness in our galactic neighborhood.

A fascinating alternative to supersymmetric dark matter arises in models with "universal" extra dimensions [10]. The premise is that all standard model fields propagate in a higher dimensional bulk that is compactified on a space whose size is about TeV^{-1} (for earlier work, see [11, 12]). Higher dimensional momentum conservation in the bulk translates into Kaluza-Klein (KK) mode number conservation in four dimensions that is broken by orbifold boundary conditions to a discrete subgroup, called KK parity. All odd-level KK modes are odd under KK parity, and therefore the lightest level-one KK particle (LKP) does not decay. The most natural candidate for the LKP is the first KK excitation of the hypercharge gauge boson, $B^{(1)}$ [12, 13, 14, 15]. In addition to being stable, neutral and colorless, the thermal relic density of $B^{(1)}$s is consistent with the measurements from WMAP when the mass of $B^{(1)}$ is in the range of hundreds of GeV up to about a TeV [15]. The precise LKP relic density depends on the mass spectrum of the level-one KK excitations, however. We will consider LKPs with masses as light as allowed by precision electroweak constraints, $m_{B^{(1)}} \gtrsim 300$ GeV [10].

Direct and indirect detection strategies for $B^{(1)}$ Kaluza-Klein Dark Matter (KKDM) have been explored [16, 17, 18, 19]. Indirect detection is particularly promising given the large dark matter mass, annihilation cross section and annihilation fraction into leptons [16, 17]. The positron flux and spectrum from annihilating KKDM was first considered in Ref. [16]. In this letter, we revisit the positron flux and spectrum specifically to explore the possibility that KKDM annihilating in the galactic halo is responsible for the positron excess observed by HEAT.

$B^{(1)}$ dark matter dominantly annihilates through t-channel exchange of other level-one KK particles. The annihilation cross section into fermions is proportional to the final state fermion's hypercharge to the fourth power. Thus right-handed leptons dominate with an annihilation fraction of 20-23% per generation for an approximately degenerate level-one KK spectrum. This means energetic ("hard") positrons are copiously produced in KKDM annihilation both directly and through cascades of muon and tau decay. The remaining annihilation fraction is primarily into right-handed up-type quarks that can also produce positrons via cascading, but mainly at lower energies.

In Fig. 1, we show the positron spectrum that results from generic particle dark matter annihilation to $\tau^+\tau^-$, $\mu^+\mu^-$, $b\bar{b}$ and gauge boson pairs. Clearly, annihilation into e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ produces a much harder spectrum than the modes that typically dominate for supersymmetric dark matter (gauge bosons or $b\bar{b}$). These initial positron spectra, including cascade decays, were

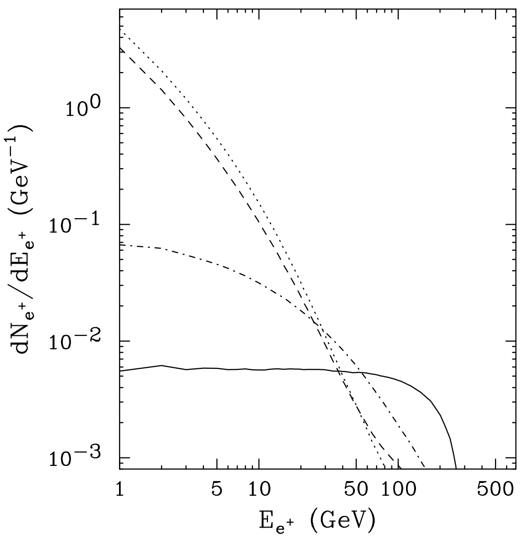

FIG. 1: The positron spectrum from generic particle dark matter annihilations, prior to propagation, for selected annihilation modes with $m_{\rm DM} = 300$ GeV. Solid, dot-dash, dotted and dashed lines correspond to the positron spectrum per annihilation into $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$ and gauge bosons, respectively. Charged lepton final states clearly produce a considerably harder spectrum of positrons than in other modes. The spectrum for annihilation into e^+e^- (not shown) is trivially a delta function at an energy equal to the dark matter particle mass.

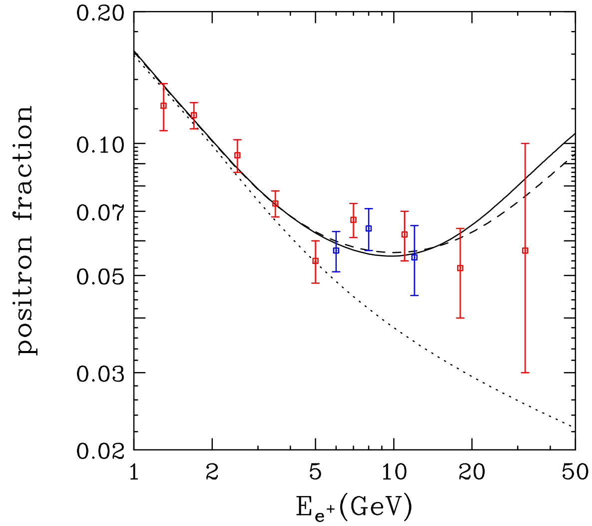

FIG. 2: The positron fraction from annihilation of KKDM is shown as a function of positron energy. The solid and dashed lines represent 300 and 600 GeV $B^{(1)}$s, respectively. The annihilation rate was treated as a free parameter, used for normalization. The dotted line represents the background predicted with no contribution from dark matter annihilation. The error bars shown are from the 1994-95 and 2000 HEAT flights. The propagation parameters $K(E_{e^+}) = 3.3 \times 10^{28} (E_{e^+}/1\,{\rm GeV})^{0.47}\,{\rm cm}^2/{\rm s}$, $b(E_{e^+}) = 10^{-16} (E_{e^+}/1\,{\rm GeV})^2$ GeV/s and $L = 4\,{\rm kpc}$ were used.

calculated using PYTHIA [20] as it is implemented in the DarkSusy package [21].

Following their production, positrons travel through the galactic halo under the influence of interstellar magnetic fields and lose energy via inverse Compton and synchrotron processes. The effects of propagation on the positron spectrum can be calculated using a standard diffusion model [7, 22]. Such a technique is limited, however, by the uncertainties in the relevant parameters, such as the diffusion constant and energy loss rate.

Cosmic ray measurements (primarily the boron to carbon ratio) indicate a diffusion constant best fit to $K(E_{e^+}) = 3.3 \times 10^{28} (E_{e^+}/1\,{\rm GeV})^{0.47}\,{\rm cm}^2/{\rm s}$ [23] with 20 to 25% uncertainties at the 1σ confidence level. For the positron energy loss rate, only a rough estimate is possible, and the value of this parameter could vary with location. We use a value for the energy loss rate of $b(E_{e^+}) = 10^{-16} (E_{e^+}/1\,{\rm GeV})^2$ GeV/s. We consider a $2L = 8$ kpc thick slab for the diffusion zone, which is the width best fit to observations [23, 24]. While we have used a modified isothermal sphere profile, we find that other profiles such as NFW produce very similar results. The effect of varying L is also small. This is because positrons, unlike gamma-rays and anti-protons, travel only a few kpc before losing their energy. For further discussion of two-zone diffusion models, see Refs. [7, 24, 25].

To minimize the effects of solar modulation, the spectrum of cosmic positrons is generally shown as a "positron fraction", or the ratio of positrons to positrons plus electrons at a given energy. We convert our positron flux to a positron fraction by using the spectrum of secondary positrons, secondary electrons and primary electrons found in Ref. [4]. This flux (without a dark matter contribution) constitutes the background to a potential signal.

The positron fraction predicted from KKDM annihilation is shown as a function of positron energy in Fig. 2. The level-one KK spectrum was assumed to be almost degenerate although we found only very slight variation for a spectrum including the effects of radiative corrections [13]. Comparing our results to the measurements of the 1994-95 and 2000 HEAT flights, it is clear that above 7-8 GeV the background-only curve fails to match the data while KKDM annihilation can provide a reasonably good fit to the data.

With substantial uncertainties in the propagation parameters, it is important to consider the effect of varying these quantities on the positron spectrum. In Fig. 3, we show the positron fraction for $m_{B^{(1)}} = 300$ GeV with various choices of the diffusion constant and energy loss rate.

To compare our propagation model and parameters with those used in other studies, we remark on two other collaborations' treatment of this problem. First, Edsjö and Baltz [7] used a considerably lower diffusion con-

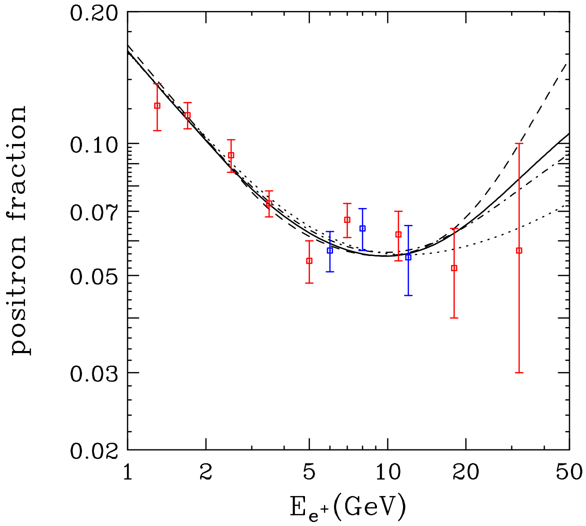

FIG. 3: The positron fraction from annihilation of KKDM for several choices of propagation parameters. The solid line represents the model with the same propagation parameters as in Fig. 2. The dashed line is for a model with an energy loss rate smaller by a factor of two. The models represented by dot-dashed and dotted lines use the full energy loss rate but diffusion constants that are 80% and 50% of the value used in Fig. 2. Lastly, the spectrum with *both* half the diffusion constant and half the energy loss rate falls almost exactly on top of the solid line. For all cases, $m_{B^{(1)}} = 300$ GeV and $L = 4$ kpc were used.

stant with a stronger energy dependence: $K(E_{e^+}) \propto E_{e^+}^{0.6}$. This was also used in the defaults of the DarkSusy package [21]. Alternatively, the more recent work by de Boer *et al.* uses a larger diffusion constant with a weaker energy dependence, $K(E_{e^+}) = 4.2 \times 10^{28}(E_{e^+}/1\,\mathrm{GeV})^{0.33}\,\mathrm{cm}^2/\mathrm{s}$, and a smaller energy loss rate $b(E_{e^+}) = 5 \times 10^{-17}(E_{e^+}/1\,\mathrm{GeV})^2$ GeV/s [9]. The net effect of these choices is a considerably harder spectrum, which helps to explain why they could find reasonable fits to the HEAT data using supersymmetric dark matter that annihilates largely to $b\bar{b}$. Finally, Ref. [22] provides a set of Green's functions for the propagation of positrons while fitting several sources of astrophysical data. We find that this technique gives a very similar spectrum.

From Figs. 2 and 3 we see that KKDM clearly fits the data considerably better than the background. In fact, for all of the variations of the parameters that we have considered, we consistently found a good fit to the data, up to normalization. In Table I, we show the χ^2 per degree of freedom of the fit to the data for several $B^{(1)}$ masses and propagation models. It is remarkable that KKDM is able to fit the spectral shape of the HEAT observations to better than χ^2=1.1 per degree of freedom in all of these cases.

The annihilation cross section of KKDM into fermions in the low velocity limit is $\langle \sigma v \rangle = 95 g_1^4/324\pi m_{B^{(1)}}^2$ [15].

Model	$\chi^2/d.o.f.$	$\mathrm{BF}_{\rho=0.3}$	$\mathrm{BF}_{\rho=0.8}$
$m = 300,\ K_0 = 3.3,\ b_0 = 1$	10.8/12	24.1	3.4
$m = 400,\ K_0 = 3.3,\ b_0 = 1$	10.1/12	66.7	9.4
$m = 500,\ K_0 = 3.3,\ b_0 = 1$	9.7/12	139.3	19.6
$m = 600,\ K_0 = 3.3,\ b_0 = 1$	9.4/12	253.8	35.7
$m = 300,\ K_0 = 3.3,\ b_0 = 0.5$	12.9/12	23.8	3.3
$m = 300,\ K_0 = 2.6,\ b_0 = 1$	10.2/12	21.6	3.0
$m = 300,\ K_0 = 1.7,\ b_0 = 1$	10.2/12	16.7	2.3
$m = 300,\ K_0 = 1.7,\ b_0 = 0.5$	10.8/12	12.1	1.7
$m = 400,\ K_0 = 3.3,\ b_0 = 0.5$	11.7/12	59.9	8.4
$m = 400,\ K_0 = 2.6,\ b_0 = 1$	9.8/12	56.3	7.9
$m = 400,\ K_0 = 1.7,\ b_0 = 1$	10.2/12	44.2	6.2
$m = 400,\ K_0 = 1.7,\ b_0 = 0.5$	10.1/12	33.4	4.7

TABLE I: The quality of the spectral fit (χ^2 per degree of freedom) and the boost factors required for various $B^{(1)}$ masses and propagation parameters. m is the mass of $B^{(1)}$ in GeV. K_0 is the diffusion constant in units of $10^{28}(E_{e^+}/1\,\mathrm{GeV})^{0.47}\,\mathrm{cm}^2/\mathrm{s}$. b_0 is the positron energy loss rate in units of $10^{-16}(E_{e^+}/1\,\mathrm{GeV})^2$ GeV/s. The columns $\mathrm{BF}_{\rho=0.3}$ and $\mathrm{BF}_{\rho=0.8}$ contain the boost factors required assuming a local dark matter density of $\rho = 0.3$ and $\rho = 0.8\,\mathrm{GeV/cm}^3$, respectively.

This is about 7 pb for $m_{B^{(1)}} = 300$ GeV. Using this cross section and a smooth dark matter halo profile (without clumps), the flux of positrons produced in dark matter annihilations can be calculated. Spatial density variations from a smooth distribution of dark matter are expected to enhance the effective annihilation rate by a factor of, perhaps, 2 to 4, but not much more [8]. This astrophysical increase in the rate is commonly called the "boost factor".

In Table I, the boost factors needed for KKDM to fit the data are shown for various $B^{(1)}$ masses and propagation parameters. The last two columns correspond to the boost factors that would be needed given a local dark matter density of $\rho = 0.3$ and $0.8\,\mathrm{GeV/cm}^3$, respectively. The first value is the best fit density, while the second value is approximately the largest density consistent with observations for a reasonable halo profile [26]. For a light LKP ($m_{B^{(1)}} = 300$ GeV), we find that the boost factor required is in the range of 12-24 for the best fit local density. Given a higher local density ($0.8\,\mathrm{GeV/cm}^3$), the boost factor required is in the range (1.7-3.4) that is well within astrophysical expectations for local dark matter clumpiness. Heavier $B^{(1)}$s require larger boost factors as illustrated for $m_{B^{(1)}} = 400$ GeV. Note that it is possible to reduce the boost factor by up to about a factor of two at the expense of worsening the fit to the HEAT observations. For a LKP heavier than about 400 GeV, the positron flux produced is likely to be too small to account for the HEAT observations without an unnaturally large degree of dark substructure.

In Ref. [15] the authors found that the relic density of

$B^{(1)}$ KKDM falls with the range measured by WMAP for $m_{B^{(1)}} = 550$ to 800 GeV. The lower value of the $B^{(1)}$ mass corresponds to a level-one KK spectrum with right-handed KK leptons only 1% heavier than $B^{(1)}$, leading to significant coannihilations. To naturally fit the HEAT observations we ideally need $m_{B^{(1)}} \lesssim 400$ GeV, and therefore, the $B^{(1)}$ relic density is naively too low by a factor of 2-3. However, variations in the KK spectrum, such as lowering the masses of the KK quarks, leads to additional coannihilation channels (which were not calculated in Ref. [15]) that can enhance the relic density and therefore lower the mass of $B^{(1)}$ needed to get the relic density up into the WMAP range. There could also be nonthermal sources of KKDM that boost the relic density. In any case, we are encouraged that the thermal relic density is at least roughly in the right range that is consistent with the $B^{(1)}$ mass range needed to explain the HEAT observations.

Future experiments, such as PAMELA and AMS-02, will be capable of measuring the cosmic positron spectrum to much higher energies and with greater precision. The confirmation in such experiments of a rise in the positron spectrum, as shown in Figs. 2 and 3, would further favor KKDM as the source of the positron excess. In addition, a distinctive spike in the spectrum at $E_{e^+} = m_{B^{(1)}}$ is expected [16] that would provide a good measurement of the $B^{(1)}$ mass. Indirect detection is also expected at next generation neutrino telescopes such as IceCube that should find between tens and a thousand events per year from KKDM annihilations in the Sun [17]. Existing neutrino telescopes, such as AMANDA-II, may potentially be sensitive to this scenario as well. Direct dark matter detection experiments are also approaching the sensitivity needed to observe such a WIMP [16, 18]. Finally, future collider experiments including the Tevatron and particularly the Large Hadron Collider (LHC) are expected to produce most of the level-one and possibly higher level KK modes that will lead to fascinating (and confusing) signals [14] in this scenario.

In conclusion, we have shown that Kaluza-Klein dark matter annihilating in the galactic halo can account for the excess in the cosmic positron spectrum observed by the HEAT experiment. We find an excellent fit to the observed positron spectrum for a wide range of positron propagation parameters and $B^{(1)}$ dark matter masses. Additionally, with reasonable values of the local dark matter density and clumpiness, the annihilation rate of 300-400 GeV Kaluza-Klein dark matter and the corresponding positron flux can be sufficient to account for the HEAT observations. This is in contrast to supersymmetric dark matter, in which an unnatural amount of dark matter substructure is invariably required to produce the necessary positron flux. If the HEAT observations are confirmed by future measurements of a rising cosmic positron spectrum from PAMELA and AMS-02, then interpreting the HEAT excess as arising from KKDM annihilation in the galactic halo implies other dark matter detection and collider experiments should soon see confirming signals of a world with extra spatial dimensions only slightly above the electroweak scale.

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